

Quarkonium+ γ production in coherent hadron - hadron interactions at LHC energies

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In this paper we study the $H + \gamma$ ($H = J/\Psi$ and Υ) production in coherent hadron - hadron interactions at LHC energies. Considering the ultrarelativistic protons as a source of photons, we estimate the $\gamma + p \rightarrow H + \gamma + X$ cross section using the non-relativistic QCD (NRQCD) factorization formalism and considering different sets of values for the matrix elements. Our results for the total $p + p \rightarrow p + H + \gamma + X$ cross sections and rapidity distributions at $\sqrt{s} = 7$ and 14 TeV demonstrate that the experimental analysis of the $J/\Psi + \gamma$ production at LHC is feasible.

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I. INTRODUCTION

In the last years, the analysis of coherent hadron-hadron collisions becomes an alternative way to study the theory of strong interactions - the Quantum Chromodynamics (QCD) - in the regime of high energies (For reviews see Ref. [1]). The basic idea in coherent hadron collisions is that the total cross section for a given process can be factorized in terms of the equivalent flux of photons in the hadron projectile and the photon-photon or photon-hadron production cross section. The main advantage of using colliding hadrons and nuclear beams for studying photon induced interactions is the high equivalent photon energies and luminosities, that can be achieved at existing and future accelerators. Consequently, studies of γp interactions at LHC provides valuable information on the QCD dynamics at high energies. The photon-hadron interactions can be divided into exclusive and inclusive reactions. In the first case, a certain particle is produced, while the target remains in the ground state (or is only internally excited). On the other hand, in inclusive interactions the particle produced is accompanied by one or more particles from the breakup of the target. The typical examples of these processes are the exclusive vector meson production, described by the process $\gamma p \rightarrow Hp$ ($H = J/\Psi, \Upsilon$), and the inclusive heavy quark production [$\gamma p \rightarrow XY$ ($X = c\bar{c}, b\bar{b}$)], respectively. The results of these studies demonstrate that their detection is feasible at the LHC (For recent discussions see, e.g. Refs. [2–4]). It motivates the analysis of the production of other final states in coherent hadron - hadron interactions.

In this paper we study, for the first time, the inclusive quarkonium + photon photoproduction in pp collisions at LHC energies. The total cross section for the process $p + p \rightarrow p \otimes H + \gamma + X$ ($H = J/\Psi$ or Υ) is given by

$$\sigma(pp \rightarrow p \otimes H + \gamma + X) = 2 \int d\omega \frac{dN_{\gamma/p}(\omega)}{d\omega} \sigma_{\gamma p \rightarrow H + \gamma + X}(W_{\gamma p}^2), \quad (1)$$

where \otimes represents a rapidity gap in the final state, ω is the photon energy, $\frac{dN_{\gamma}}{d\omega}$ is the equivalent photon flux, $W_{\gamma p}^2 = 2\omega\sqrt{S_{NN}}$ and $\sqrt{S_{NN}}$ is the c.m.s energy of the hadron-hadron system. The photon spectrum of a relativistic proton is given by [5],

$$\frac{dN_{\gamma/p}(\omega)}{d\omega} = \frac{\alpha_{em}}{2\pi\omega} \left[1 + \left(1 - \frac{2\omega}{\sqrt{S_{NN}}} \right)^2 \right] \left(\ln \Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3} \right), \quad (2)$$

with the notation $\Omega = 1 + [(0.71 \text{ GeV}^2)/Q_{\min}^2]$, $Q_{\min}^2 = \omega^2/[\gamma_L^2(1 - 2\omega/\sqrt{S_{NN}})] \approx (\omega/\gamma_L)^2$ and γ_L is the Lorentz boost of a single beam. Distinctly from the exclusive vector meson photoproduction discussed in, e.g., Ref. [3], which is characterized by two rapidity gaps in the final state, in our case it is characterized by one rapidity gap associated to the photon emitted by one of the protons and the remnants of the other proton. The main input in our calculations is the $\gamma + p \rightarrow H + \gamma + X$ cross section, which we estimate using the non-relativistic QCD (NRQCD) factorization formalism [6]. Recent results demonstrate that this formalism is able to describe quite well the RHIC and HERA data for the hadroproduction and photoproduction of charmonium in terms of an universal set of matrix elements and that the inclusion of the color octet processes is indispensable to describe the photoproduction data [7].

This paper is organized as follows. In next section we present a brief review about the quarkonium+ γ photoproduction in the NRQCD formalism. In Section III we present our predictions for the rapidity distributions and total cross sections for $J/\Psi + \gamma$ and $\Upsilon + \gamma$ production at LHC energies. Finally, in Section IV, we summarize our main conclusions.

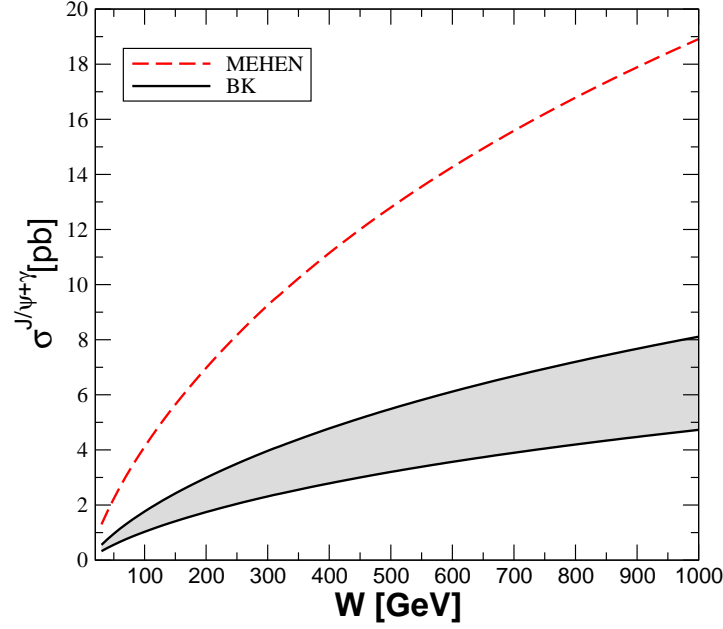


FIG. 1: Energy dependence of the total $J/\Psi + \gamma$ photoproduction cross section considering two different sets of matrix elements (see text).

II. THE QUARKONIA+ γ PHOTOPRODUCTION

In the NRQCD formalism the cross section for the production of a heavy quarkonium state H factorizes as $\sigma(ab \rightarrow H + X) = \sum_n \sigma(ab \rightarrow Q\bar{Q}[n] + X) \langle \mathcal{O}^H[n] \rangle$, where the coefficients $\sigma(ab \rightarrow Q\bar{Q}[n] + X)$ are perturbatively calculated short distance cross sections for the production of the heavy quark pair $Q\bar{Q}$ in an intermediate Fock state n , which does not have to be color neutral. The $\langle \mathcal{O}^H[n] \rangle$ are nonperturbative long distance matrix elements, which describe the transition of the intermediate $Q\bar{Q}$ in the physical state H via soft gluon radiation. Currently, these elements have to be extracted in a global fit to quarkonium data as performed, for instance, in Ref. [8]. It is important to emphasize that the underlying mechanics governing heavy quarkonium production is still subject of intense debate (For a recent review see, e.g., Ref. [9]).

In the specific case of the $H + \gamma$ photoproduction, the total cross section can be expressed as follows [10]

$$\sigma(\gamma + p \rightarrow H + \gamma + X) = \int dz dp_\perp^2 \frac{xg(x, \mu^2)}{z(1-z)} \frac{d\sigma}{dt}(\gamma + g \rightarrow H + \gamma) \quad (3)$$

where $z \equiv (p_H \cdot p)/(p_\gamma \cdot p)$, with p_H , p and p_γ being the four momentum of the quarkonium, proton and photon, respectively. In the proton rest frame, z can be interpreted as the fraction of the photon energy carried away by the quarkonium. Moreover, p_\perp is the magnitude of the quarkonium three-momentum normal to the beam axis. The partonic differential cross section $d\sigma/dt$ is given by [10]

$$\frac{d\sigma}{dt}(\gamma + g \rightarrow H + \gamma) = \frac{64\pi^2 e_Q^4 \alpha^2 \alpha_s m_Q}{3 s^2} \left(\frac{s^2 s_1^2 + t^2 t_1^2 + u^2 u_1^2}{s_1^2 t_1^2 u_1^2} \right) \langle \mathcal{O}_8^V(^3S_1) \rangle \quad (4)$$

where e_Q and m_Q are, respectively, the charge and mass of heavy quark constituent of the quarkonium. The Mandelstam variables can be expressed in terms of z and p_\perp as follows:

$$\begin{aligned} s &= \frac{p_\perp^2 + (2m_Q)^2(1-z)}{z(1-z)}, \\ t &= -\frac{p_\perp^2 + (2m_Q)^2(1-z)}{z}, \\ u &= -\frac{p_\perp^2}{1-z}. \end{aligned} \quad (5)$$

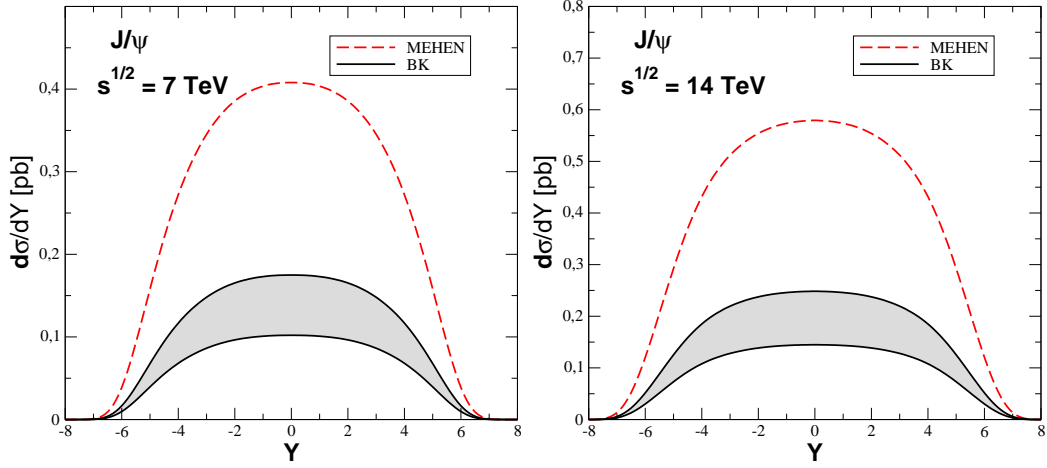


FIG. 2: Rapidity distribution for the $J/\Psi + \gamma$ photoproduction in pp collisions at $\sqrt{s} = 7$ TeV (left panel) and 14 TeV (right panel) considering two different sets of values for the matrix elements.

Moreover, $s_1 = s - 4m_Q^2$, $t_1 = t - 4m_Q^2$, $u_1 = u - 4m_Q^2$ and the Bjorken variable x can be expressed by

$$x = \frac{p_\perp^2 + (2m_Q)^2(1-z)}{W_{\gamma p}^2 z(1-z)}, \quad (6)$$

where $W_{\gamma p}$ is the photon - proton center-of-mass energy. In our calculations we consider the gluon distribution as given by the CTEQ6 parametrization [11].

III. RESULTS

In what follows we present our results for the $H + \gamma$ photoproduction in coherent hadron - hadron collisions at LHC energies. One of the main uncertainties in our predictions is associated to the NRQCD matrix elements. For the J/Ψ case, we consider the more recent global fit performed in Ref. [8] (denoted BK hereafter), and its uncertainties, which obtain that $\langle O_8^{J/\psi}(^3S_1) \rangle = 2.24 \pm 0.59 \times 10^{-3} \text{ GeV}^3$. For comparison, we also use the value previously considered in Ref. [10] (denoted MEHEN hereafter): $\langle O_8^{J/\psi}(^3S_1) \rangle = 6.6 \times 10^{-3} \text{ GeV}^3$. Although this choice is outdated, we keep it in order to estimate the dependence of the matrix elements in our results for the $J/\Psi + \gamma$ production in coherent interactions. As show in Fig. 1 these two choices imply very distinct results for the $J/\Psi + \gamma$ photoproduction cross section, with the latter being an upper bound for the total cross section. The cross section increases with the energy, which is directly associated to the x -behaviour of the gluon distribution. It is important to emphasize that while studies of photoproduction at HERA were limited to photon-proton center of mass energies of about 200 GeV, photon-hadron interactions at LHC can reach one order of magnitude higher on energy. For instance, if we consider pp collisions at LHC, the Lorentz factor is $\gamma_L = 7455$, giving the maximum c.m.s. γp energy $W_{\gamma p} \approx 8390 \text{ GeV}$. Consequently, the analysis can also be useful to constrain the proton gluon distribution. (For related studies see Ref. [12]). We postpone a more detailed study of this topic for a forthcoming publication.

For the Υ case, we also use two different sets of values for the matrix elements. The first one taken from Ref. [13] (denoted BSV hereafter), which obtain $\langle O_8^\Upsilon(^3S_1) \rangle = 5.3 \times 10^{-3} \pm 0.5 \text{ GeV}^3$ from fits to CDF data for bottomonium production. The second one we taken from Ref. [14] (denoted BFL hereafter) which obtain $\langle O_8^\Upsilon(^3S_1) \rangle = 0.02 \text{ GeV}^3$.

Lets now calculate the rapidity distribution and total cross sections for $H + \gamma$ production in coherent proton - proton collisions at $\sqrt{s} = 7$ and 14 TeV. The distribution on rapidity Y of the produced final state can be directly computed from Eq. (1), by using its relation with the photon energy ω , i.e. $Y \propto \ln(\omega/m_H)$. Explicitly, the rapidity distribution is written down as,

$$\frac{d\sigma [p + p \rightarrow p \otimes H + \gamma + X]}{dY} = \omega \frac{dN_{\gamma/h_1}(\omega)}{d\omega} \sigma_{\gamma h_2 \rightarrow H + \gamma + X}(\omega) + \omega \frac{dN_{\gamma/h_2}(\omega)}{d\omega} \sigma_{\gamma h_1 \rightarrow H + \gamma + X}(\omega), \quad (7)$$

where we taken into account that the two protons can be the source of the photons ($h_1 = h_2 = p$) and X is a hadronic final state resulting of the fragmentation of the proton target. The rapidity gap \otimes is associated to the proton which emits the photon and remains intact. In Fig. 2 we present our results for the $J/\Psi + \gamma$ production considering the two

$J/\Psi + \gamma$	MEHEN	BK
LHC (7 TeV)	3.62 pb	1.23 ± 0.50 pb
LHC (14 TeV)	5.60 pb	1.90 ± 0.32 pb
$\Upsilon + \gamma$	BFL	BSV
LHC (14 TeV)	5.46 fb	1.45 ± 0.13 fb

TABLE I: The total cross section for the $H + \gamma$ photoproduction in coherent hadron - hadrons collisions at LHC energies.

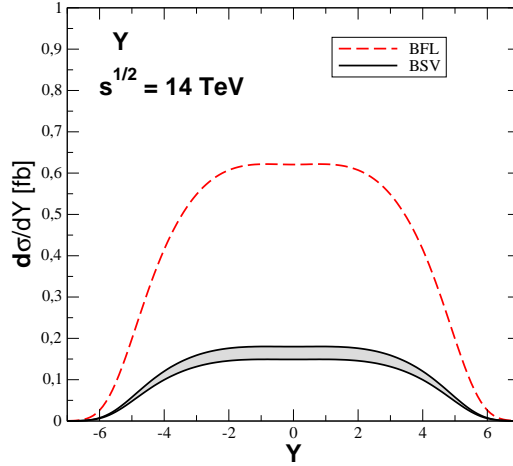


FIG. 3: Rapidity distribution for the $\Upsilon + \gamma$ photoproduction in pp collisions at $\sqrt{s} = 14$ TeV considering two different sets of values for the matrix elements.

different sets of values for the matrix elements and two different center-of-mass energies. As the photoproduction cross section is proportional to the cross section, our predictions for the rapidity distribution increases with the energy. Moreover, as expected from Fig. 1, the predictions obtained using the MEHEN matrix element [10] implies a value for rapidity distribution at $Y = 0$ which is a factor ≈ 3 larger than that using the BK one. This large difference is also observed in the predictions for the total cross section (See Table I). It demonstrates that the study of this observable can be useful to constrain the matrix element. Assuming the design luminosity $\mathcal{L} = 10^7 \text{ mb}^{-1}\text{s}^{-1}$ the corresponding event rates will be $\approx 1 \times 10^5$ (2×10^5) events/years at $\sqrt{s} = 7$ (14) TeV for the BK matrix elements.

In Fig. 3 and Table I we present our predictions for the $\Upsilon + \gamma$ production considering the two different sets of values for the matrix elements and $\sqrt{s} = 14$ TeV. As observed in the J/Ψ case, the predictions are strongly dependent on the matrix elements used in the calculations. However, in the Υ case the cross sections are a factor 10^3 smaller than those obtained for $J/\Psi + \gamma$ production, which implies that the event rates will be $\approx 1 \times 10^2$ events/years, making the experimental analysis of this final state a hard task.

Lets discuss the experimental separation of the $H + \gamma$ photoproduction and compare our predictions with those obtained for the inclusive production or considering diffractive (Pomeron) interactions. In comparison to the inclusive hadroproduction (See e.g. [15]), which is characterized by the process $p + p \rightarrow X + H + \gamma + Y$, with both proton producing hadronic final states, the photoproduction cross sections are a factor $\approx 10^3$ smaller. However, as in photoproduction we have a rapidity gap in the final state, the separation of the signal from hadronic background would be relatively clear since the event multiplicity for photoproduction interactions is lower, which implies that it may be used as a separation factor between these processes. Another mechanism which also is characterized by one rapidity gap in the final state, is the single diffractive $H + \gamma$ production. This process was analysed, e.g., in Refs. [16, 17], considering that the Pomeron has a partonic structure. In comparison with those results, our predictions are a factor ≈ 8 smaller. However, it is expected that emerging hadrons from Pomeron processes have a much larger transverse momentum than those resulting from photoproduction processes. Consequently, in principle it is possible to introduce a selection criteria to separate these two processes. Moreover, it is important to emphasize that Pomeron predictions are strongly dependent on the value used for the gap survival factor, while our results should not be modified by soft absorption corrections.

IV. CONCLUSIONS

In this paper we have computed for the first time the cross sections for photoproduction of quarkonium+ γ in coherent pp collisions at LHC energies using the NRQCD formalism and considering two different sets of values for the matrix elements. Such processes are interesting since the final state is characterized by a low multiplicity and one rapidity gap. Moreover, the produced large p_T quarkonia are relatively easy to detect through their leptonic decay modes and their transverse momenta are balanced by the associated high energy photon. Our results demonstrate that the rapidity distributions and total cross sections are strongly dependent on the magnitude of the matrix elements. Moreover, we predict sizeable for the $J/\Psi + \gamma$ cross section, which makes the experimental analyses of this process feasible at LHC.

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